Supporting Information: Waveguide Nanowire Superconducting Single-Photon Detectors Fabricated on GaAs and the Study of Their Optical Properties

Döndü Sahin[1,*], Alessandro Gaggero[2], Jan Willem Weber[1], Ivan Agafonov[1], Marcel A. Verheijen[1], Francesco Mattioli[2], Johannes Beetz[3], Martin Kamp[3], Sven Höfling (Member) [3], Mauritius C. M. v. d. Sanden[1], Roberto Leoni[2] and Andrea Fiore[1]

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[1]*COBRA Research Institute, Eindhoven University of Technology, PO Box 513, 5600 MB Eindhoven, The Netherlands*

[2]*Istituto di Fotonica e Nanotecnologie, CNR, Via Cineto Romano 42, 00156 Roma, Italy*

[3]*Technische Physik, Physikalisches Institut and Wilhelm Conrad Röntgen Research Center for Complex Material Systems, Universität Würzburg, Am Hubland, D-97074 Würzburg, Germany*

* To whom the correspondence and request for materials should be addressed: E-mail: d.sahin@bristol.ac.uk

1- Set-up and measurement of coupling efficiency

For the measurement of the NbN superconducting nanowire detectors integrated on GaAs ridge waveguides, a continuous flow cryostat is used in all the experiments. As the optical and electrical inputs are realized via probes thermally anchored to the cold finger, it reaches a base temperature of 2.1K. Figure S1 gives a simplified schematic look into the cryostat (only the optical interface is shown for simplicity).

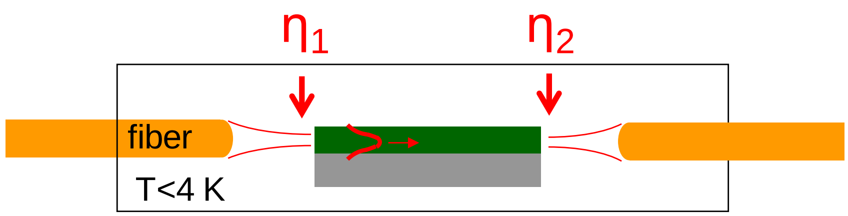

Figure S1: Simplified schematic of the waveguide μ-probe setup used for characterization of the waveguide nanowire superconducting single-photon detectors. The configuration shows the transmission measurement from which the coupling efficiency (η_c) is calculated, where $\eta_1 = \eta_2 = \eta_c$.The GaAs and AlGaAs layers are shown in green and grey, respectively.

In this figure, a configuration for transmission measurements is depicted. A GaAs ridge waveguide without nanowire on top is mounted in the cryostat and two identical lensed fibers (spot size of 2.5±0.5 μm at $1/e^2$) are used in order to measure transmission by varying the wavelength around 1310 nm. Therefore, we assume that the coupling efficiencies at the two facets are equal (see figure S1), $\eta_1 = \eta_2 = \eta_c$. The coupling efficiency η_c is defined as the fraction of power coupled from the lensed fiber into the waveguide mode and can be derived from the measured Fabry-Perot fringes in the transmission spectra through the waveguide. From standard Fabry-Perot theory, we calculate the transmittance (T) through the waveguide as

$$T = \eta_c^2 \frac{e^{-\alpha L}}{1 + R^2 e^{-2\alpha L} - 2Re^{-\alpha L}\cos(2kL)}$$

where the maxima and the minima of the transmittance are calculated by using the equations,

$$T_{\max} = \eta_c^2 \frac{e^{-\alpha L}}{(1 - Re^{-\alpha L})^2} \text{ and } T_{\min} = \eta_c^2 \frac{e^{-\alpha L}}{(1 + Re^{-\alpha L})^2}$$

where R is the reflectivity at the waveguide end facet, α is the attenuation coefficient in the waveguide and L is the waveguide length. R is calculated using the effective modal index of the waveguide mode for each polarization and L is measured. In addition, T_{max} and T_{min} are obtained by averaging the maximum and minimum values of the Fabry-Perot transmittance fringes, respectively.

By dividing these two measured quantity, T_{max}/T_{min}, the attenuation coefficient, α, is calculated from

$$\alpha = -\frac{1}{L}\ln\left(\frac{1}{R}\frac{\sqrt{T_{\max}/T_{\min}} - 1}{\sqrt{T_{\max}/T_{\min}} + 1}\right)$$ and the coupling efficiency, η_c, is calculated from $$2\frac{\sqrt{T_{\max}T_{\min}}}{T_{\max} + T_{\min}} = \eta_c e^{-\alpha L/2}.$$

2- Design of Superconducting Nanowire Waveguide Single-Photon Detectors

In the manuscript we have discussed several designs based on ridge waveguide and nanobeam geometries. The calculated effective indices of the corresponding waveguides are summarized in table S1 for the fundamental transverse electric (TE) and transverse magnetic (TM) modes at 1310 nm. For each design, the reflection at the interface between the passive waveguide and the waveguide with nanowires is calculated as negligible.

The first two designs are based on a multi-mode GaAs waveguide. The first design with NbN nanowires on top of 300 nm GaAs is optimized to provide a high absorption by the nanowires for the TE polarized mode as the quantum dots in GaAs also emit in this same mode. However, for this design, as shown in Figure S2 (left), the lowest-order quasi-TM mode has a complex distribution of the electric field polarization. Therefore, the coupling from the TM-polarized mode of the input fiber was very inefficient. However, by increasing the GaAs thickness only by 50 nm, this TM mode profile shows a more uniform polarization with larger overlap with a TM-polarized Gaussian beam (see Figure S2 (right)). The nanobeam structure, on the other hand, is a single-mode waveguide and provides a higher modal absorption coefficient (see Table S1).

Table S1: Effective modal indices for several designs at λ=1310 nm.

Design	$\tilde{n}_{eff}^{TE}$	$\tilde{n}_{eff}^{TM}$
NbN on 300 nm-thick GaAs core layer	3.1443 – i0.0039	3.0928 – i0.0036
NbN on 350 nm-thick GaAs core layer	3.1788 – i0.0033	3.1304 – i0.0041
NbN on 300 nm-thick nanobeam	2.7438 – i0.00997	2.4575 – i0.0329
WSi on 300 nm-thick nanobeam	2.7562 – i0.0139	2.4964 – i0.0397

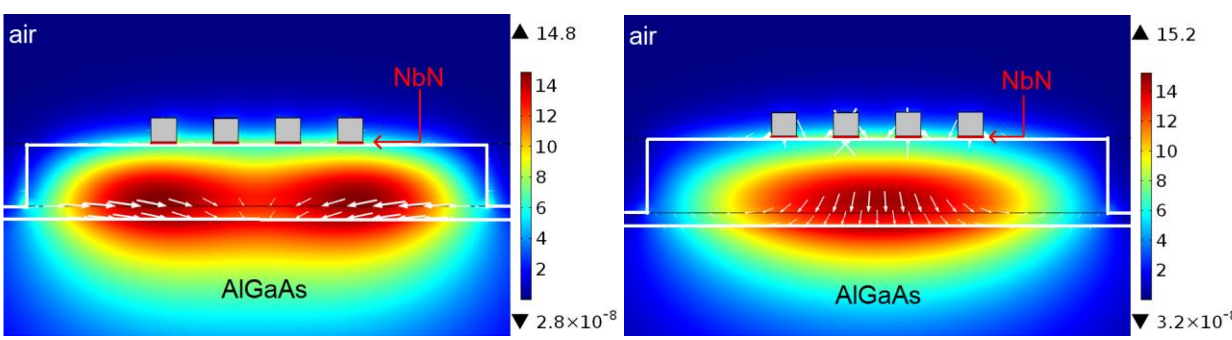

Figure S2: Contour and vector plots of the electric field for the fundamental quasi-TM mode for NbN nanowire on top of (left) a GaAs (300 nm)/AlGaAs ridge waveguide and (right) a GaAs (350 nm)/AlGaAs ridge waveguide. The waveguide structure is shown as a white contour, the NbN nanowires are colored in red and the SiOx on top of NbN nanowires in grey.